PHENIX Measurements of Higher-order Flow Harmonics in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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Abstract.
Flow coefficients v_n for $n = 2, 3, 4$, characterizing the anisotropic collective flow in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, are presented. They indicate the expected growth of viscous damping for sound propagation in the quark gluon plasma (QGP) produced in these collisions. Hydrodynamical model comparisons which include the effects of initial state geometry fluctuations, highlight the role of higher harmonics ($v_{n,n>2}$) as a constraint for disentangling the effects of viscosity and initial conditions, and suggest a small specific viscosity for the QGP. This viscosity is compatible with that obtained via a newly proposed technique [6] which employs the relative magnitudes of v_n to estimate the viscosity, and the "viscous horizon" or length-scale which characterizes the highest harmonic that survives viscous damping.

1. Introduction

Measurements of anisotropic flow in heavy-ion collisions at the Relativistic Heavy Ion collider (RHIC), continue to play a central role in ongoing efforts to characterize the transport properties of the quark gluon plasma (QGP) produced in these collisions. Recently, considerable attention has been given to extractions of the specific viscosity η/s [the ratio of viscosity (η) to entropy density (s)] via elliptic flow (v_2) measurements. These extractions indicate a range of 1-2 times the conjectured lower bound [2] for η/s, (*i.e.* $4\pi\frac{\eta}{s} \sim 1-2$). This large uncertainty (100%) is known to be dominated by the uncertainty in model estimates of the initial eccentricity [3, 4]. Thus, a more precise extraction of η/s requires the development of new experimental constraints.

Because of the acoustic nature of flow (*i.e.* it is driven by pressure gradients), a transparent way to evaluate the strength of dissipative effects, is to consider the attenuation of sub-horizon sound modes in the plasma. In the presence of viscosity (η), sound intensity is exponentially damped as : $\delta T_{\mu\nu}(t) = \exp\left(-\frac{2}{3}\frac{\eta}{s}\frac{k^2 t}{3T}\right)\delta T_{\mu\nu}(0)$ [5], where the spectrum of initial (t = 0) perturbations of the energy-momentum tensor $T_{\mu\nu}$, can be associated with the harmonics of the shape deformations and density fluctuations of the collision zone; k is the wave number for these harmonics, and t and T are the expansion time and the temperature of the plasma respectively. Since viscous damping scales as k^2 the viscous corrections for the eccentricity driven harmonics v_n (with wavelengths $2\pi\bar{R}/n$ for $n \geq 1$, *i.e.* $k \sim n/\bar{R}$), are expected to scale as n^2K; $\bar{R}$ is the transverse

size of the collision zone and K is the Knudsen number [6]. The latter is often used to parametrize viscous corrections. The length scale r_v or *"viscous horizon"* separates the sound wavelengths which are effectively damped out, from those which are not, and $k_v = 2\pi/r_v$ is linked to the order (n_v) of the highest harmonic which survives viscous damping. Thus, the relative magnitudes of the higher-order harmonics ($v_{n,n\geq 3}$) are expected to provide additional constraints on both the magnitude of η/s and the "best" model for eccentricity determinations [5, 7, 10]. Here, we report new v_n measurements [1] and investigate their utility as constraints for precision extraction of η/s.

2. Data analysis and results

The results presented are derived from $\sim 3.0 \times 10^9$ Au+Au events obtained during the 2007 RHIC running period. The Fourier coefficients v_n were obtained via (i) pair-wise distributions in the azimuthal angle difference ($\Delta\phi = \phi_a - \phi_b$) between particles with pseudorapidity separation $\Delta\eta' > 1$ and transverse momenta p_T^a and p_T^b (respectively); $\frac{dN^{pairs}}{d\Delta\phi} \propto \left(1 + \sum_{n=1} 2v_n^a(p_T^a)v_n^b(p_T^b)\cos(n\Delta\phi)\right)$, and (ii) azimuthal distributions $\frac{dN}{d\phi} \propto (1 + \sum_{n=1} 2v_n \cos(n\phi - n\Psi_n))$, of charged hadrons detected in the PHENIX central arms at an azimuthal angle ϕ, relative to event planes Ψ_n [11] obtained with three separate detectors: Beam-Beam Counters (BBC), Reaction-Plane Detectors (RXN), and Muon Piston Calorimeters (MPC). Each detector has a North (South) component which allows correlation studies between sub-event planes Φ_n determined at forward (backward) rapidity. The absolute pseudorapidity coverage for these detectors are $3.1 < \left|\eta'_{\mathrm{BBC}}\right| < 3.9$, $1.0 < |\eta'_{\mathrm{RXN}}| < 2.8$ and $3.1 < \left|\eta'_{\mathrm{MPC}}\right| < 3.7$.

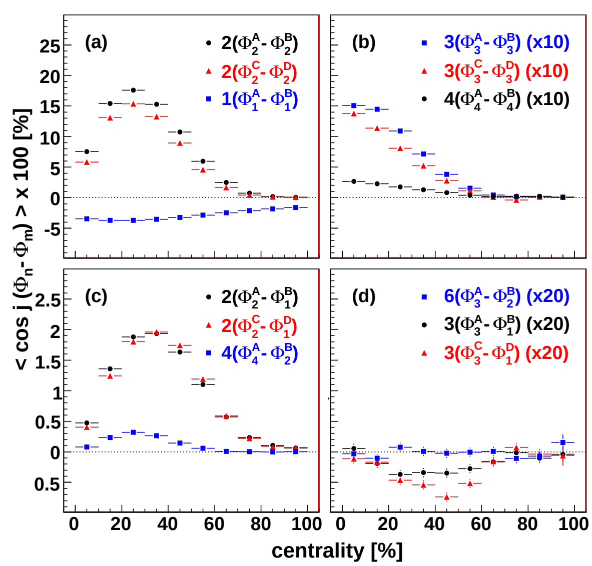

Figure 1. Correlation strengths of the event planes for various detector combinations as a function of collision centrality. The detectors in which the event plane is measured are: RXN North (A), BBC South (B), MPC North (C) and MPC South (D).

Figure 1 shows the centrality dependence of the correlation strength

$\left\langle \cos(j(\Phi_n^A - \Phi_m^B)) \right\rangle$ for sub-event combinations (A, B) involving different event-plane detectors with $\Delta\eta' \sim 5$ and $\Delta\eta' \sim 7$. Note that the order j is chosen to account for the n-multiplet of directions $(2\pi/n)$ of Φ_n and the magnitudes for $\left\langle \sin(j(\Phi_n^A - \Phi_m^B)) \right\rangle$ are consistent with zero for all centrality, j, and Φ combinations. Positive sub-event correlations are indicated in panels (a) and (b) for $\Psi_{2,3,4}$, with sizable magnitudes for $\Psi_{2,3}$ and much smaller values for Ψ_4. The negative correlation indicated in panel (a) is due to the well known antisymmetric pseudorapidity dependence of sidewards flow (v_1), as well as momentum conservation. The expected correlation between Ψ_1 and Ψ_2, and that between Ψ_2 and Ψ_4 are confirmed in panel (c); they show that Ψ_1, Ψ_2 and Ψ_4 are correlated with the reaction plane. An initial state fluctuation origin of Ψ_3 [and hence v_3] is well supported by the absence of a correlation between Ψ_2 and Ψ_3 in panel (d). The absence of a correlation between Ψ_2 and Ψ_3 reflects the rather large fluctuations of Ψ_3 about Ψ_2 and gives a null value for v_3 measured relative to Ψ_2 [8].

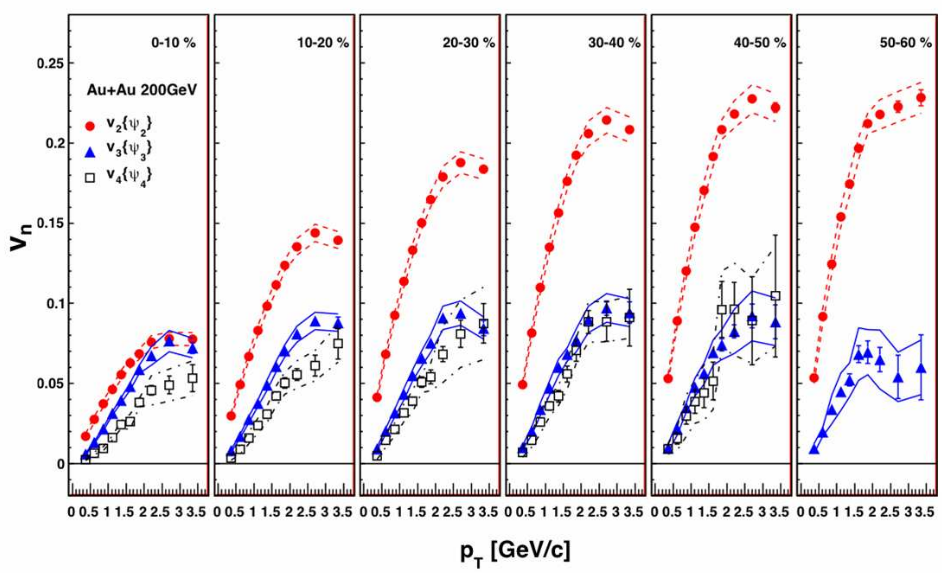

Figure 2. v_n vs. p_T for several centrality bins as indicated.

Figure 2 shows a clear growth of v_2 from central to mid-peripheral collisions, and a near constancy of v_3 and v_4 which are strong indicators of the role of initial state fluctuations in establishing the higher harmonics. It is noteworthy that the ratios $v_3/(v_2)^{3/2}$ and $v_4/(v_2)^2$ are essentially independent of p_T (for $p_T < 2.5 - 3.0$ GeV/c) but do increase rapidly from peripheral to central collisions. These scaling patterns have been interpreted as an indication that viscous damping for the higher harmonics follow the expected acoustic (or n^2K) scaling [6]. Interestingly, these scaling patterns are also reflected in quark number (n_q) scaling of particle identified data. That is, $v_n/(n_q)^{n/2}$ for different particle species, plotted as a function of transverse kinetic energy KE_T, gives essentially a single curve as illustrated for $v_3/(n_q)^{3/2}$ in the left panel of Fig. 3. The centrality dependence of $v_3/(v_2)^{3/2}$ and $v_4/(v_2)^2$ also provide a valuable constraint for eccentricity models [6]; they favor a Glauber initial eccentricity model.

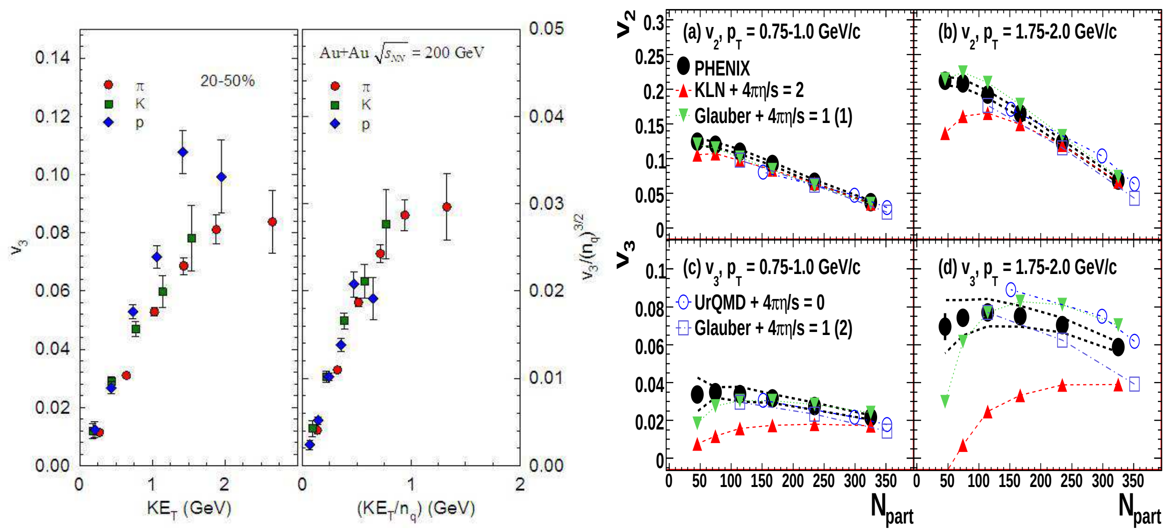

Figure 3. Illustration of quark number scaling for v_3 (left). Comparisons of $v_n\{\Psi_n\}$ vs. N_{part} with theory as indicated (right).

The right panels of Fig. 3 compare the centrality dependence of $v_2\{\Psi_2\}$ and $v_3\{\Psi_3\}$ with several hydrodynamical model calculations [9, 10], which demonstrates an essential constraint that the data provide. Panel (a) shows good agreement between data and calculations which employ MC-Glauber and MC-KLN initial eccentricities (ε_2) paired with viscosity values of $4\pi\frac{\eta}{s} = 1$ and 2, respectively. The resulting η/s uncertainty ($\sim$ 100%) reflect the model dependence of ε_2. Differences between the calculations become more apparent for the higher p_T selection shown in panel (b), but the implied uncertainty for η/s remains large. Panels (c) and (d) demonstrates the utility of $v_3\{\Psi_3\}$ as a constraint for disentangling the effects of viscosity and initial conditions; they indicate excellent agreement with the results from viscous hydrodynamics which employ Glauber initial eccentricities and $4\pi\frac{\eta}{s} = 1$, and rather poor agreement with calculations which employ MC-KLN initial conditions and $4\pi\frac{\eta}{s} = 2$. The constraining power of $v_3\{\Psi_3\}$ stems from the fact that viscous corrections to v_n scale as n^2 and the two eccentricity models give similar values for ε_3 [7]. Thus, the larger viscosity needed for agreement with the data with MC-KLN eccentricities in panels (a) and (b), leads to a significant under prediction of $v_3\{\Psi_3\}$ in panels (c) and (d). In summary, PHENIX v_n measurements provide important constraints for robust extraction of η/s.

References

[1] A. Adare *et al.* [PHENIX Collaboration], arXiv:1105.3928 [nucl-ex].
[2] P. Kovtun, D. T. Son and A. O. Starinets, Phys. Rev. Lett. **94**, 111601 (2005)
[3] H. Song, S. A. Bass, U. Heinz, T. Hirano and C. Shen, Phys. Rev. Lett. **106**, 192301 (2011)
[4] R. A. Lacey *et al.*, Phys. Rev. C **82**, 034910 (2010)
[5] P. Staig and E. Shuryak, arXiv:1008.3139 [nucl-th]; E. Shuryak, these proceedings.
[6] R. A. Lacey, A. Taranenko, N. N. Ajitanand and J. M. Alexander, arXiv:1105.3782 [nucl-ex].
[7] R. A. Lacey, R. Wei, N. N. Ajitanand and A. Taranenko, Phys. Rev. C **83** (2011) 044902
[8] R. A. Lacey, R. Wei, N. N. Ajitanand, J. M. Alexander, J. Jia and A. Taranenko, arXiv:1011.3535.

[9] B. Schenke, S. Jeon and C. Gale, Phys. Rev. Lett. **106**, 042301 (2011)
[10] B. H. Alver, C. Gombeaud, M. Luzum and J. Y. Ollitrault, Phys. Rev. C **82**, 034913 (2010)
[11] J. Y. Ollitrault, Phys. Rev. D **46** (1992) 229.